Nonlinear Stress Analysis of Titanium Implants by Finite Element Method

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With use of dental implants on the rise, there is also a tandem increase in the number of implant fracture reports. To the end of investigating the stress occurring in implants, elasticity and plasticity analyses were performed using the finite element method. The following results were obtained:

(1) With one-piece type of implants of 3.3 mm diameter, elasticity analysis showed that after applying 500 N in a 45-degree direction, stress exceeding 500 MPa — which is the proof stress of grade 4 pure titanium — occurred. This suggested the possibility of fatigue destruction due to abnormal occlusal force, such as during bruxism.

(2) With two-piece type of implants that can tolerate vertical loading of 5,000 N, plasticity analysis suggested the possibility of screw area fracture after applying 500 N in a 45-degree direction.

(3) On the combined use of an abutment and a fixture from different manufacturers, fracture destruction of even Ti-6Al-4V, which has a high degree of strength, was predicted.

Key words: Finite element method, Titanium implant, Nonlinear stress analysis

INTRODUCTION

With use of dental implants unabatedly on the rise, there is also a tandem increase in the number of implant fracture reports1-2). Perennially, implant success is of utmost concern and importance to all patients at all times. Against this backdrop, strength analyses and fatigue tests have been performed to predict and determine the clinical performance of dental implants3-7).

In particular, for restoration with ITI implants (Φ: 3.3 mm, L: 12 mm, pure titanium: grade 4), Merz et al. of the Institute Straumann performed fatigue tests to analyze the fatigue resistance of implant-abutment connectors8). They reported that fatigue destruction occurred when force larger than 380 N was applied in a 30-degree direction. They also reported that fatigue strength differed among original titanium lots.

Differences in fatigue strength among original material lots are due to differences in the residual degree of process distortion, as we have previously reported9). Therefore, many cases of implant fracture, as shown in Fig. 1, were due to insufficient understanding of the non-uniform mechanical strengths of implants caused by non-uniformity of original materials, as well as due to limitation on mechanical strength as imposed by load application angle.

In this study, nonlinear stress analysis using the finite element method was performed with twofold purposes: (1) to investigate the stress occurring in implants caused by occlusal forces; and (2) to assess the limitation on mechanical strength as imposed by load application angle on implants.

MATERIALS AND METHODS

Analytical methods

Analysis was performed using a finite element method program (ANSYS Inc., Canonsburg, PA, USA). Since the elastic modulus and Poisson’s ratio of pure titanium are almost the same as those of titanium alloy10), a model with unified abutment and implant areas (one-piece type) was produced for the purpose of performing elasticity analysis. In addition, a model in which the abutment and implant areas were separated into two pieces (two-piece type) was produced to perform nonlinear plasticity analysis.

Analytical model

Grade 2 (G2) pure titanium implant (Φ: 3.3 mm, 4 mm) (Yoshioka, Yokohama, Japan) was selected as
In addition, G2 pure titanium implant and Ti-6Al-4V alloy abutment (Nitto Kogyo, Nagoya, Japan) were also combined as an analytical model. Each analytical model was divided into approximately 30,000 three-dimensional elements as shown in Fig. 2. Since human maximum occlusal force is almost the same as human body weight (approximately 50-80 kgf), 500 N was applied to the abutment head area vertically and in the directions of 12.5, 30, and 45 degrees. Assuming that abutment and implants are connected by friction, the compact bone's basal area was fixed.

**Physical properties**

Table 1 shows the values of the physical properties of materials used for elasticity analysis. Grade 2 (G2) and grade 4 (G4) pure titanium and Ti-6Al-4V alloy were used as original implant materials.

Figure 3 shows a true stress-true strain curve of the titanium material used for plasticity analysis. The true stress-true strain curve was obtained from a stress-strain curve and the diameter of fractured area after a tension test of a titanium round rod (G2 Ti-6Al-4V alloy: Kobe Steel Ltd., Kobe, Japan; G4: L. Klein SA, Bienne, Switzerland). The latter was used for implant production by Yoshioka (Yoshioka, Yokohama, Japan), and tension test was carried out using a test machine (Model 5882, Instron, Canton, USA).

As the main purpose of this study was to analyze the strength of implants, the jawbone was regarded as the compact bone and being elastic in property.

**Evaluation of the validity of analyses**

To evaluate the validity of analyses, an implant manufactured by Yoshioka (Yoshioka, Yokohama, Japan) was fixed using a jig, and load test was...
performed by applying a prescribed load using a test machine (AG-500D, Shimadzu, Kyoto, Japan). After load application, the implant was longitudinally sectioned using a polishing machine (ECOMET3, Buehler, Lake Bluff, USA) and the sectioned area was compared with analysis results.

RESULTS

Elasticity analysis

Figure 4 shows the deformation and distribution of first main stress in a general one-piece type of implant of 3.3 mm diameter after a vertical application of 500 N. The amount of deformation is indicated by actual length, and the amount of stress is indicated by contours. With a vertical load application, stress applied to one-piece type of implant was only approximately 100 MPa or smaller.

Figure 5 shows the deformation and distribution of first main stress in a one-piece type of implant of 3.3 mm diameter after applying 500 N in a 45-degree direction. Stress exceeding 500 MPa, which is the proof stress of G4 pure titanium, occurred in this case.

Figure 6 shows the deformation and distribution of first main stress in a one-piece type of implant of 4.0 mm diameter after applying 500 N in a 45-degree direction. In this case, stress decreased to approximately 320 MPa.

Plasticity analysis

Figure 7 shows the deformation and distribution of...
von Mises stress in a G2 pure titanium, two-piece type of implant of 3.3 mm diameter after a vertical application of 500 N. With two-piece type of implant, stress of approximately 150 MPa was concentrated in the abutment screw area, showing a higher stress concentration compared with one-piece type of implant.

Figure 8 shows the deformation and distribution of von Mises stress in a G2 pure titanium, two-piece type of implant of 3.3 mm diameter after applying 500 N in a 45-degree direction. Concentration of stress exceeding 550 MPa was noted in the abutment neck area, superior margin of the bearing area, and superior margin of the compact bone, with evident indication of large deformation. Conversely, in Fig. 5, the amount of elastic deformation was very little as most of the deformation was plastic deformation.

Figures 9 and 10 show the deformation and distribution of von Mises stress in a G2 pure titanium, two-piece type of implant of 3.3 mm diameter after applying 500 N in 12.5- (Fig. 10) and 30-degree (Fig. 9) directions. Maximum stress applied to the implant decreased to 400 MPa at the angle of 30 degrees, and 300 MPa at the angle of 12.5 degrees. A slight deformation occurred in the screw area at the angle of 12.5 degrees.

Figure 11 shows the deformation and distribution of von Mises stress in a G2 pure titanium, two-piece type of implant of 4.0 mm diameter after applying 500 N in a 45-degree direction.
type of implant of 4.0 mm diameter after applying 500 N in a 45-degree direction. Maximum stress decreased to 390 MPa or lower, and deformation was slight.

Figure 12 shows the deformation and distribution of von Mises stress in a G4 pure titanium, two-piece type of implant of 3.3 mm diameter after applying 500 N in a 45-degree direction. Although deformation was smaller than in G2, stress exceeding 550 MPa was concentrated in the abutment neck and bearing areas.

Figure 13 shows the deformation and distribution of von Mises stress in an implant, which was a combination of a G2 pure titanium implant of 3.3 mm diameter and an abutment (Ti-6Al-4V alloy) manufactured by Nitto Kogyo, after applying 500 N in a 45-degree direction. Stress exceeding 1 GPa, which is larger than the proof stress of 900 MPa of Ti-6Al-4V alloy, was concentrated in the abutment neck area.

Evaluation of the validity of analyses
Experimental versus analysis results are compared in Fig. 14. Figure 14A shows the longitudinal section of an implant manufactured by Yoshioka, to which no load was applied. Figure 14B-1 shows the longitudinal section of the implant after a vertical application of 5,000 N. Figure 14B-2 shows the analysis results in G2 implant after a vertical application of 5,000 N. Figure 14C-1 shows the longitudinal section of the G2 implant after applying 500 N in a 45-degree direction. Figure 14C-2 shows the analysis results in G2 implant after applying 500 N in a 45-degree direction. Although the implant head area was greatly crushed after a vertical application of 5,000 N according to the analysis results, it was because friction by the pressure plate of the autograph was not considered, and analysis results were markedly in accordance with experimental results.

DISCUSSION
As shown in Fig. 14, the analysis results in this study were markedly in accordance with the experimental results. On this basis, our analysis results were sufficiently reliable to discuss the limitation imposed on implants' mechanical strength due to load application angle.

As shown in Figs. 4 and 7, current implants have
enough strength to bear the vertical loading of occlusal forces. However, as shown in Fig. 5, even in a one-piece type of implant that is the strongest structurally, an application of 500 N in a 45-degree direction to the implant of 3.3 mm diameter resulted in stress exceeding 500 MPa — which is the proof stress of G4 pure titanium. This result suggested that since the fatigue strengths of titanium and titanium alloy are almost the same as the proof stress, titanium implants of 3.3 mm diameter in any structural morphology may cause fatigue destruction.

On the other hand, when the diameter was 4.0 mm, as shown in Fig. 6, maximum stress decreased to 320 MPa. This finding thus suggested that whereas it is impossible for G2 pure titanium — with a proof stress of approximately 250 MPa — to bear the maximum occlusal force of the molars, G4 pure titanium can do so adequately.

Plasticity analysis results showed that whereas G2 pure titanium could bear the load of 500 N when load application direction was within 12.5 degrees (Fig. 10), G4 pure titanium could up the ante by bearing the same load even when the direction was 30 degrees (Fig. 9). Nonetheless, fatigue destruction resulted for G4 pure titanium when load application direction was 45 degrees (Fig. 12). When the diameter was 4.0 mm (Fig. 11), maximum stress was greatly decreased — but the possibility of fatigue destruction remained high for G2 pure titanium.

When G2 pure titanium implant and Ti-6Al-4V abutment, which are products of different manufacturers, were combined (Fig. 13), markedly large stress concentration occurred in the abutment neck area — thereby indicating a higher possibility of fatigue destruction. One example of implant fracture is shown in Fig. 1, and this fracture occurred due to this combination. Therefore, although it is mechanically possible to combine implants and abutments of different manufacturers, fit of the junction area cannot be obtained and stress is concentrated in the screw area. With explicit suggestion of a high fracture risk, combined use of implants and abutments of different manufacturers is therefore not recommended.

CONCLUSIONS

Elasticity and nonlinear stress analyses were performed using the finite element method for twofold purposes: (1) to investigate the stress occurring in implants caused by occlusal forces; and (2) to assess the limitation on mechanical strength as imposed by load application angle on implants. The following conclusions were obtained:

(1) When an occlusal force of 500 N was applied to implants of 3.3 mm diameter in a 45-degree direction, stress exceeding 500 MPa — which is the proof stress of G4 pure titanium — occurred even in one-piece type of implants which have no combined structures.

(2) Since all grades of pure titanium have almost the same elastic modulus, possibility of fatigue destruction is present in all types of titanium implants such as Bräemark and ITI. Therefore, use of these implants warrants attention and vigilant carefulness.

(3) Since structural design of titanium implants involves limitation of strength, careless use may result in easy fracture.

(4) Combined use of implants and abutments of different manufacturers is contraindicated, since the possibility of fatigue destruction is markedly high.

REFERENCES


